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Modeling wildfire risk to northern spotted owl (*Strix occidentalis* caurina) habitat in Central Oregon, USA

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Abstract

Natural disturbances including wildfire, insects and disease are a growing threat to the remaining late successional forests in the Pacific Northwest, USA. These forests are a cornerstone of the region's ecological diversity and provide essential habitat to a number of rare terrestrial and aquatic species including the endangered northern spotted owl (*Strix occidentalis* caurina). Wildfires in particular have reduced the amount of late successional forests over the past decade, prompting land managers to expand investments in forest management in an attempt to slow losses and mitigate wildfire risk. Much of the emphasis is focused specifically on late successional reserves established under the Northwest Forest Plan to provide habitat for spotted owls. In this paper, we demonstrate a probabilistic risk analysis system for quantifying wildfire threats to spotted owl habitat and comparing the efficacy of fuel treatment scenarios. We used wildfire simulation methods to calculate spatially explicit probabilities of habitat loss for fuel treatment scenarios on a 70,245 ha study area in Central Oregon, USA. We simulated 1000 wildfires with randomly located ignitions and weather conditions that replicated a recent large fire within the study area. A flame length threshold for each spotted owl habitat stand was determined using the forest vegetation simulator and used to predict the proportion of fires that resulted in habitat loss. Wildfire modeling revealed a strong spatial pattern in burn probability created by natural fuel breaks (lakes and lava flows). We observed a non-linear decrease in the probability of habitat loss with increasing treatment area. Fuels treatments on a relatively minor percentage of the forested landscape (20%) resulted in a 44% decrease in the probability of spotted owl habitat loss averaged over all habitat stands. The modeling system advances the application of quantitative and probabilistic risk assessment for habitat and species conservation planning.
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Keywords: Wildfire risk; Expected loss; Northern spotted owl; Wildfire simulation; Forest vegetation simulator; FlamMap; Conservation planning

1. Introduction

The Northwest Forest Plan was developed and implemented to sustain biological diversity in the Pacific Northwest, USA, via a network of late successional forest reserves (USDA Forest Service and USDI Bureau of Land Management, 1994; Lint, 2005). Management of the forest reserves is focused on the habitat requirements for the endangered northern spotted owl (*Strix occidentalis* caurina), although the reserves are a surrogate for a wide array of other old growth dependent species, and are a cornerstone of the region's ecological diversity. Since the plan was implemented, the rate of spotted owl habitat loss from timber harvest has declined sharply. However, stand replacing wildfire and other disturbances continue to erode the habitat network, especially in the interior dry forests environments east of the Cascade Mountains (Courtney et al., 2004; Lint, 2005; Spies et al., 2006). Wildfire accounted for 75% of the disturbance-caused loss of spotted owl habitat between 1994 and 2003 (Courtney et al., 2004). Decades of fire suppression and selective timber harvesting practices (Agee, 1993; Hessburg and Agee, 2003; Wright and Agee, 2004) have led to a buildup of ladder and surface fuel, and the potential for severe, stand replacing wildfires. Under the current management trajectory, the future trend for the late successional reserves appears to be continued tree mortality, increased fuel accumulation and further stand replacement wildfire events (Mendez-Treneman, 2002; Hummel and Calkin, 2005; Lee and Irwin, 2005).

There is broad consensus among forest managers and scientists that fuel treatment including mechanical thinning

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and prescribed fire may improve the long-term protection of old growth stands from wildfire losses (Agee, 2002; Spies et al., 2006) and a number of strategies have been proposed to address wildfire risk at the stand and landscape level (Spies et al., 2006). However, the efficacy of fuel treatment beyond the individual stand scale remains an experimental topic (Finney, 2001; Finney et al., 2006). Furthermore, stand treatment to mitigate long-term wildfire damage may carry significant short-term adverse effects to nesting spotted owls (Carey et al., 1992; Zabel et al., 1995; North et al., 1999; Bond et al., 2002; Lee and Irwin, 2005). The paradox of managing the dry forest of the east cascades for dense multistoried stands favored by spotted owls has been examined in several papers (Agee, 2002; Lee and Irwin, 2005; Spies et al., 2006). Wildfire risk mitigation for spotted owl habitat has been explored with simulation models in several case studies (Wilson and Baker, 1998; Hummel and Calkin, 2005; Roloff et al., 2005). However, these and related studies have yet to yield operational tools for quantifying the probability of habitat loss from wildfire and the potential benefits, if any, of mitigation efforts. As elaborated in Finney (2005), empirical data on fire size distribution in the western USA support the argument that large fire spread is a major determinant of wildfire probability. For instance, on the Deschutes National Forest in Central Oregon, USA, where ca. 90,000 ha of lands are managed to preserve and create late successional forests, the historical record for mapped fires (>1.18 ha) between 1908 and 2003 shows that a mere 10% of the fires accounted for 74% of the total burned area (156,648 ha). These data indicate that the probability that a given stand will experience a fire is primarily a question of large fire spread rather than local fuel conditions. Thus, wildfire risk analysis must account for spatial patterns of wildfire spread over areas comparable to recent large wildfires. Furthermore, since risk is the probability of actual loss or gain (Society for Risk Analysis, 2006), a wildfire risk model must also consider fire intensity and effect to be a useful tool for assessing the potential impact of fire on landscape attributes.

In this paper, we describe a wildfire risk analysis system for quantifying potential wildfire impacts on spotted owl habitat and measuring the efficacy of landscape fuel treatment on reducing risk. We used the formal definition of risk (Brillinger, 2003; Society for Risk Analysis, 2006; Kerns and Ager, 2007), defined for wildfire as the product of: (1) the probability of a fire at a specific intensity and location, and (2) the resulting change in financial or ecological value (Finney, 2005; Scott, 2006). The risk assessment was tested on a 70,245 ha study area on the Deschutes National Forest in Central Oregon that contains a 19,888 ha late successional forest reserve managed under the Northwest Forest Plan for spotted owl habitat. The risk analysis system has broad application for conservation planning and biodiversity management where natural disturbances like wildfire pose a long-term threat to habitat management objectives, and the efficacy of mitigation strategies are in question.

2. Materials and methods

2.1. Study area

The Five Buttes Interface planning area is located 80 km south of Bend, Oregon, and contains 60,867 ha of land managed by the Deschutes National Forest (henceforth the Forest) and 9378 ha of private lands (Fig. 1). The area was identified by forest managers and staff for a fuel reduction project to mitigate wildfire hazard to the Davis Late Successional Reserve (LSR) and other resources in the area (Fig. 1). The site is within the high lava plain physiographic and geological province of Central Oregon, characterized by young lava flows and scattered cinder cones and lava buttes (Franklin and Dyrness, 1988). The vegetation varies considerably with elevation, topography and substrate, with the relatively flat pumice plains dominated by dense stands of lodgepole pine (*Pinus contorta*). Vegetation on the buttes gradually changes with elevation, with ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) growing below approximately 2000 m, and white fir (*Abies concolor*), mountain hemlock (*Tsuga mertensiana*) and western white pine (*Pinus monticola*) growing between about 2200 and 2400 m. In the western, higher elevation portion of the study area (>2400 m), mountain hemlock, western white pine and lodgepole pine are the most common tree species. Old growth ponderosa pine forests in this area had a natural fire return interval of 4–11 years and fires were low severity. Fire frequency was considerably lower in the mesic mountain hemlock forests at higher elevations, with return intervals in the range of 50–200 years, and fires that were generally high severity, stand replacing events (Spies et al., 2006).

Approximately, 80% of the study area is administered according to the Northwest Forest Plan, including the Davis Late Successional Reserve (19,888 ha) where management goals are to sustain and create forest habitat for the spotted owl (Fig. 1). Wildfire and other disturbances are frequent within the study, most notably the June, 2003 Davis fire which burned 8268 ha, including 24% of the Davis Late Successional Reserve, two spotted owl home ranges and 2267 ha of spotted owl habitat. A recent assessment by the forest noted that the most immediate need within the late successional reserve was to reduce the loss of existing late and old structured stands that are imminently susceptible to insect attack or wildfire. This finding and other threats to late successional forests within the study area led to the initiation of the Five Buttes Interface fuel treatment project and motivated the present study.

2.2. Vegetation and fuels data

Vegetation and fuels data were obtained from existing forest inventory databases. Forest stands in the study area were defined using operational forest planning GIS layers and included a total of 5292 polygons. The average polygon size was 13.3 ha, ranging from a minimum of 3 ha to a maximum of 1515 ha. The forest inventory database was created using a

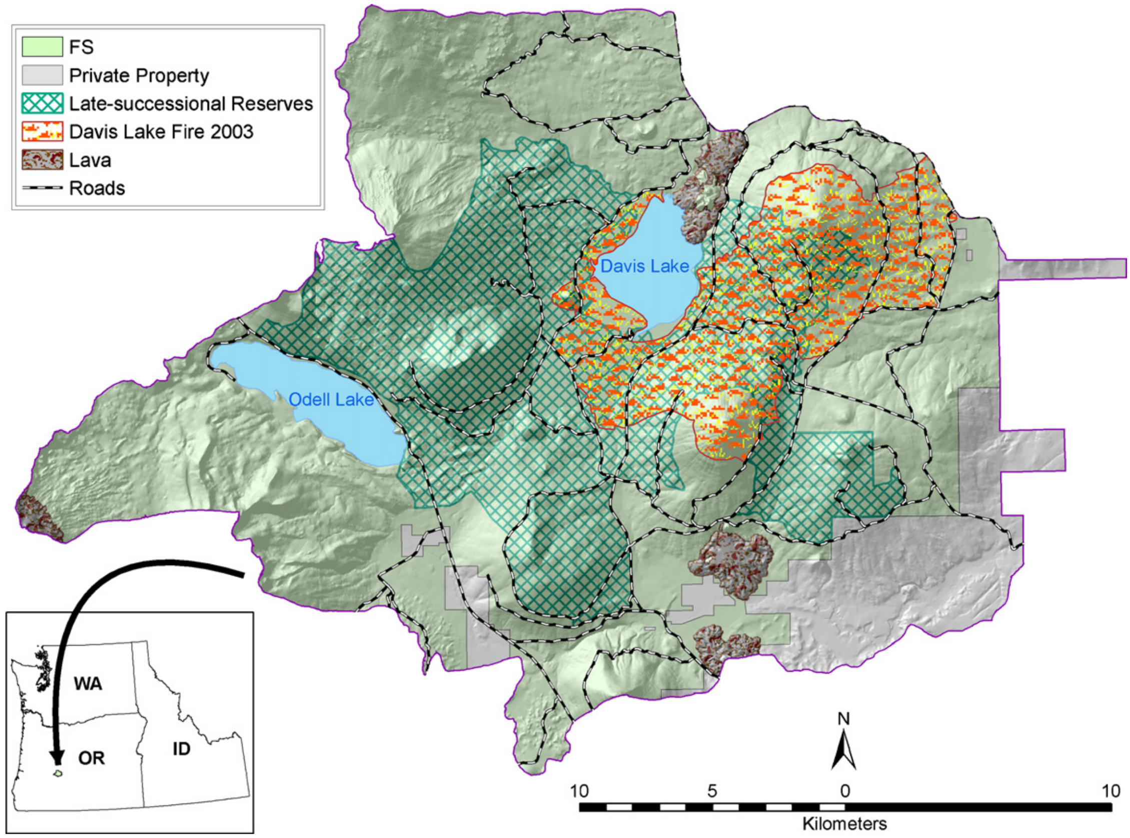

Fig. 1. Map of the 70,245 ha Five Buttes study area showing management boundaries and major features. The Davis Late Successional Reserve was created under the Northwest Forest Plan. The 8268 ha Davis fire burned in 2003 and consumed 24% of the Davis reserve.

most similar neighbor procedure (Crookston et al., 2002) where 571 inventory plots were imputed to the 5292 stands in the study area. The imputation procedure used a 2001 Landsat 5 scene and topographic indices derived from digital elevation data. Each inventory plot was used for 8.68 other stands on average (range = 1–251). The resulting database contained tree list data including diameter, density and species of trees in each stand, along with biophysical attributes including slope, aspect and elevation. Summaries of the imputed data were reviewed by forest staff as part of operational planning and compared to field observations and 1:12,000 color aerial photography. The data were then formatted according to forest vegetation simulator (FVS) requirements (Crookston et al., 2006).

2.3. Fuel treatment simulation

Fuel treatments were simulated on individual stands using the Southern Oregon variant of FVS (Dixon, 2003). The Fire and Fuels Extension to FVS (FVS-FFE, Reinhardt and Crookston, 2003) and the Parallel Processing Extension (FVS-PPE, Crookston and Stage, 1991) was invoked for additional functionality as described below. FVS is an individual-tree, distance-independent growth and yield model that is extensively used to model fuel treatments and other stand management activities. FVS simulations and processing of outputs were automated within ArcGIS (Chang, 2004; Ager et al., 2006).

The treatment constraints and priorities were modeled within FVS-PPE. Specifically, we simulated six treatment scenarios patterned after operational practices in consultation with forest managers and staff. Treatment area varied from 0% to 50% of the forested lands in 10 percentile increments (TRT-0, TRT-10, TRT-20, TRT-30, TRT-40 and TRT-50). A treatment priority variable was calculated for each stand and used in the simulation to strategically locate treatments to slow fire spread into the inventoried spotted owl habitat stands. We assumed a wind direction of 210° azimuth as part of the fire weather scenario patterned after the Davis fire. The treatment priority was calculated for each stand was calculated as:

$$\text{PRIORITY} = \frac{1}{(\text{ABS}(\text{AZOWL} - 210)/\text{DIST})}$$

where PRIORITY is the numerical ranking of stand treatment priority, AZOWL the azimuth (degrees) from the centroid of the stand being evaluated to the centroid of the nearest spotted owl habitat stand and DIST is the distance (m) from the centroid of the stand being evaluated to nearest spotted owl habitat stand.

When simulated in FVS-PPE the priority values created treatment zones adjacent to existing habitat and on the windward side in the assumed direction of approaching wildfires (Fig. 2). Stands considered for treatment with the spatial priority scheme also had to exceed stand density index thresholds as explained below to qualify for treatment. The total

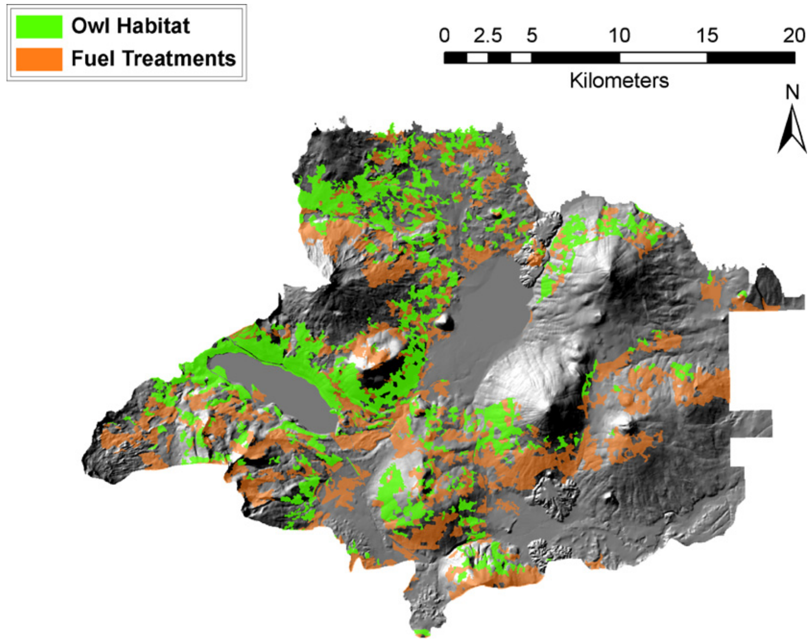

Fig. 2. Map of the Five Buttes study area showing stands classified as owl habitat in the present study, and the stands selected for treatment in the TRT-20 scenario using the spatial treatment priority calculations described in the text. Stands considered for treatment with the spatial priority scheme also had to exceed stand density index thresholds to qualify for treatment.

area treated was controlled by the treatment constraint associated with each scenario.

The FVS simulated fuel treatment prescription called for thinning from below, followed by site removal of surface fuels and underburning, thereby reducing both surface and ladder fuels and reducing crown density (Agee and Skinner, 2005). Treatments were triggered when the stand density index (SDI) exceeded 65% of the maximum SDI for each plant community type as defined by Cochran et al. (1994). Stands were thinned to a target SDI of 35% of the maximum for the stand. The thinning prescriptions favored the retention of early seral species such as ponderosa pine and Douglas-fir. Underburning and mechanical treatment of surface fuels was simulated with the FVS-FFE keywords SIMFIRE and FUELMOVE (Reinhardt and Crookston, 2003). The surface fuel treatments simulated the removal of 90% of the 7.6–14.8 cm and 40% of the 2.5–7.6 cm surface fuels. Underburning was simulated using weather conditions and fuel moisture guidelines provided by forest fuels specialists. Although the treatment prescription did not precisely replicate field practices in the entire study area, the simulations represent a highly detailed landscape modeling of fuel treatment. The FVS-PPE simulations were performed on a 1600 mHz single processor PC and required about 60 min per scenario.

Polygon data on canopy bulk density (kg/m^3), height to live crown (ft), total stand height (ft), canopy cover (%) and fuel model (Scott and Burgan, 2005) generated from FVS-FFE were used to build a raster (30 m $\times$ 30 m) landscape file in the format required by FlamMap (Finney, 2006). Slope (%) and aspect (degrees) data also required by FlamMap were calculated from USGS digital elevation data on file at the Deschutes National Forest. We replaced the fuel model calculated by FVS-FFE for treated stands with a fuel model TL1 (Scott and Burgan, 2005) after observing that the Southern Oregon variant of FVS-FFE assigned fuel models 2 (grass) or 5 (shrub) to treated stands. Neither fuel model reflected expected fire behavior under post-treatment conditions within the study area.

2.4. Wildfire simulations

For each treatment scenario, we simulated 1000 fires with randomly located ignitions and burn conditions that replicated the two 12-h spread events during the Davis fire. Specifically, we simulated a 24 h burn period with a wind speed of 48 km and wind azimuth of 210°. Fuel moisture data were obtained from Forest staff. Wildfires were simulated using minimum travel time fire growth algorithms of Finney (2002) as implemented in FlamMap (Finney, 2006; Finney et al., 2006). Fire growth is calculated while holding environmental conditions constant, exposing the effects of topography and arrangement of fuels on fire growth. The simulations were performed on a UNISYS 7000 with 16 XEON processors with a Microsoft Windows Server 2003 operating system. The wildfire simulations were performed at 90 m resolution to accelerate processing time, and required 4 h to process each scenario. Preliminary simulations showed that 1000 fires with 24-h burn periods and the assumed weather conditions described above resulted in at least one fire on about 95% of the study area, excluding non-burnable land (Davis and Odell Lakes, lava beds, cinder cones). Ignitions on these latter areas were not considered in the calculations.

Simulations conducted to replicate the Davis fire with FlamMap generated a fire perimeter of similar shape, although the size of the fire was about 70% of the size of the actual fire perimeter. Two factors contributed to the difference, one being that FlamMap does not model spotting behavior, which accelerated crown fire spread during the Davis fire. Second, some 10–15% of the area within the fire perimeter resulted from burn out operations as part of fire suppression efforts that we did not simulate.

2.5. Wildfire spread pattern

FlamMap was also used to simulate spread of a single large wildfire through the study area to generate maps of the major wildfire flow paths and arrival time (Finney, 2006). This simulation used the same weather conditions as described above and a linear ignition extending across the southwest edge of the study area. The simulation replicates a large wildfire entering the study area and spreading until all pixels are burned. The minimum travel time algorithm in FlamMap calculates the fastest fire paths and arrival time among equally spaced nodes on the landscape. The fire path calculations can be summarized to reveal the major flow paths (Fig. 2 in Finney, 2006). Flow paths were used to identify the effect of topography, lakes and other landscape features on wildfire spread (Finney, 2006) and were calculated using the 500 m default interval in FlamMap.

2.6. Estimating burn probability

Outputs from the wildfire simulations included the burn probability for each pixel, defined as the number of times a pixel burned as a proportion of total number of fires and a frequency distribution of flame lengths observed for each pixel in 0.5 m classes over all simulated fires. The burn probability for a given pixel is an estimate of the likelihood that a pixel will burn given a random ignition within the study area and burn conditions similar to the Davis fire. Burn probability is not an estimate of the future likelihood of a wildfire and should not be confused with empirical wildfire occurrence probabilities like those estimated in Brillinger et al. (2006) and similar studies.

2.7. Estimating the probability of habitat loss

The conditional probability of habitat loss for each pixel was defined as the proportion of simulated fires in each pixel that eliminated the required spotted owl habitat characteristics. Spotted owl habitat has been defined many ways in the literature, and the present study used a relatively simple definition obtained from Forest specialists. Suitable spotted owl habitat was defined as a stand that had at least one Douglas-fir tree per 0.40 ha, with a diameter at breast height (DBH, 147 cm above ground) greater than 86.36 cm, at least one snag per 0.40 ha with a DBH greater than 40.64 cm and at least 40% canopy closure. Based on the inventory data, 9178 ha in the study area met the habitat criteria. This included stands both within and outside of the Davis Late Successional Reserve that was established in the Northwest Forest Plan.

We defined the probability of habitat loss as the proportion of simulated fires that eliminated spotted owl habitat. A threshold flame length was determined for each stand above, which the fire would result in the loss of one or more of the spotted owl habitat criteria. Each stand in the study area was burned within FVS-FFE under a pre-defined flame length ranging from 0.5 to 15 m in 0.5 m increments (SIMFIRE and FLAMEADJ keywords in FVS-FFE). FVS-FFE uses several fire behavior models as described in Andrews (1986), Van Wagner (1977) and Scott and Reinhardt (2001) to predict fire spread, intensity and crown fire initiation. Tree mortality following fire is predicted according to the methods implemented in FOFEM (Reinhardt et al., 1997). The post-wildfire stand tree list was then examined to determine the threshold flame length at which habitat criteria were lost. The resulting stand-specific threshold flame length was assigned to all pixels within a stand. The proportion of total fires on each pixel that exceeded the flame length threshold was defined as the conditional probability of habitat loss. We considered the probability conditional since it represents a subset of the probability that a fire of any intensity occurs on a given pixel.

To calculate wildfire risk for each scenario according to the risk equation of Finney (2005)

$$\text{expected}[\text{net value change}] = \sum_{i=1}^{N}\sum_{j=1}^{N} p(F_i)[B_{ij} - L_{ij}]$$

where $p(F_i)$ is defined as the probability of the ith fire behavior at a specific location over N fires and B_{ij} and L_{ij} are the benefits and losses afforded for the jth value of M values received from the ith fire behavior. The expected net value change (E(NVC)) can include financial, ecological or other values at present day or future discounted values. In the present study, wildfire benefits were not considered and loss was measured by area of spotted owl habitat. Since we only consider losses, we simplify E(NVC) to expected loss, denoted as E(loss). The calculation of expected loss is the product of conditional probability of habitat loss and the area of habitat summed over all pixels. Since the pixels were equal area, the calculation was further reduced to the product of the mean conditional probability and the habitat area. The expected loss represents the area of habitat (ha) that would be eliminated from a random ignition location and conditions similar to the Davis fire.

3. Results

3.1. Wildfire size

The average wildfire size for the 1000 simulated wildfires on the untreated landscape (TRT-0) was 1680 ha (Table 1). Wildfire size for the TRT-0 scenario ranged from a maximum of 7210 ha to a minimum of 5 ha. Frequency distribution of fire sizes generated from the wildfire simulations (Fig. 3) revealed that many of the ignitions resulted in relatively small fires (<1000 ha) compared to the 8268 ha Davis fire. Many of the small fires resulted from ignitions on the northern edge of the study area where fires encountered the study area boundary. Many of the fires were effectively stopped by lakes and lava beds within the study area and spread slowly via lateral flanking and backing fire behavior. Ignitions in the central portion of the

Table 1
Outputs for wildfire size, burn probability and expected habitat loss for six fuel treatment scenarios simulated on the Five Buttes study area

Scenario	Average fire size (ha)	Maximum fire size (ha)	Average probability of burn	Average probability of burn within owl habitat	Probability of habitat loss	Expected loss (ha)
TRT-0	1680	7210	0.0135	0.0274	0.0237	218
TRT-10	1230	6012	0.0097	0.0195	0.0166	152
TRT-20	978	4317	0.0076	0.0154	0.0133	122
TRT-30	789	4050	0.0059	0.0146	0.0124	114
TRT-40	591	3793	0.0041	0.0117	0.0099	92
TRT-50	419	3066	0.0028	0.0087	0.0088	81

study area encountered the Davis fire perimeter and where spread rates on the recently burned area were dramatically reduced compared to the unburned portion of the study area. Although our initial FlamMap simulations of the Davis fire ignition generated wildfires of comparable size (e.g., 7000–8000 ha), the vast majority of ignitions in the simulations were not capable of generating fires as large as the Davis fire. This finding suggests that conditions for a large wildfire event are rare within the study area.

The average wildfire size among simulations decreased from 1680 to 419 ha between the TRT-0 and TRT-50 scenarios (Table 1). The maximum wildfire sizes also steadily decreased with increasing treatment area, from 7210 ha for the TRT-10 scenario to 3066 ha for the TRT-50 scenario. Average wildfire size decreased with increasing fuel treatment area at an average rate of about 25 ha for every percentile of treated area (Table 1). On a proportional basis, treating 20% of the forested landscape (12,695 ha) reduced the average wildfire size by about 27%. Relatively large treatment effects on wildfire size were observed at the lower treatment levels (TRT-10, TRT-20, Table 1).

Among the simulated fires, ignition location had a substantial effect on the resulting fire size (Fig. 4). For instance, for the TRT-0 scenario, ignitions on the south side of Odell Lake generated fires less than 1000 ha, while ignitions on the southern and southeastern portion of the study area resulted in fires over 7000 ha in size (Fig. 4). Examination of surface and canopy fuels where large fires were generated showed that much of the area contained overstocked stands of lodgepole pine in fuel model 10 (Anderson, 1982), which has a relatively high rate of spread. Ignitions on the northern boundary of the study area generated small fires due to the boundary effect.

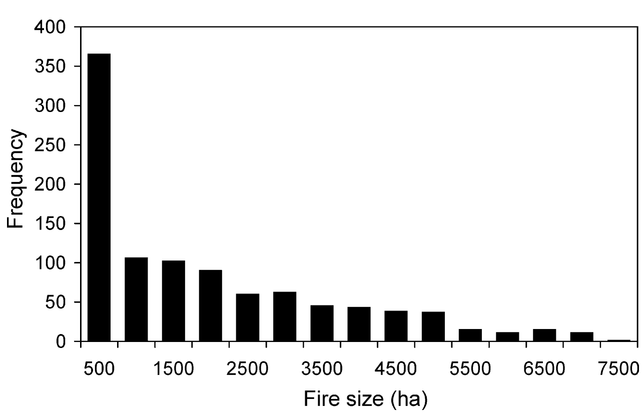

Fig. 3. Frequency distribution of fire sizes resulting from the simulation of 1000 randomly located ignitions within the study area. Data are for the TRT-0 scenario where fuel treatment was not simulated. Attempted ignitions on non-burnable features (water, rock) are not included in the figure.

3.2. Wildfire intensity

The flame length frequency distribution for each pixel obtained from FlamMap was used to calculate the area burned by flame length interval (Table 2). The calculations were performed for the TRT-0 and TRT-20 scenarios to compare overall trends in flame lengths on moderately treated versus untreated landscapes. Only pixels that experienced at least one wildfire were included in these calculations. For the TRT-0 scenario, the average fire had a flame length less than 0.5 m on 21.5% of the area burned, and the flame length was less than 3.0 m on 91.6% of the area burned (Table 2). The area burned with flame lengths larger than 4 m was less than 2%. The distribution of flame lengths for the TRT-20 scenario was similar to the TRT-0 scenario (Table 2), the largest difference being a 6.5% increase in the <0.5 m interval (Table 2). Thus, after treating 20% of the forested landscape, we observed an 6.5% increase in the area with low flame lengths. The effect of the treatments on flame length distribution was similar for spotted owl habitat stands as the study area as a whole (Table 2).

3.3. Owl habitat loss function

The FVS simulations to determine flame length thresholds for owl habitat indicated that loss of the spotted owl habitat criteria was pronounced even at low flame lengths (Fig. 5). For instance, 54% of the total habitat (4956 ha) was eliminated by fires with flame lengths <0.5 m. All spotted owl habitat was lost when fires were simulated with a 2.5 m flame length. Examination of the post fire stand conditions revealed that in all cases the canopy criteria (40% minimum) was eliminated prior to the requirements for large Douglas-fir trees and snags as flame length was increased. In general, fire susceptibility of the canopy closure criteria was due to mortality in the understory.

3.4. Burn probability and flow paths

Burn probability on a pixel basis ranged from 0.0 to 0.10 and averaged 0.0135 for the TRT-0 scenario (Table 1). Spatial variation in burn probability was pronounced (Fig. 6), with

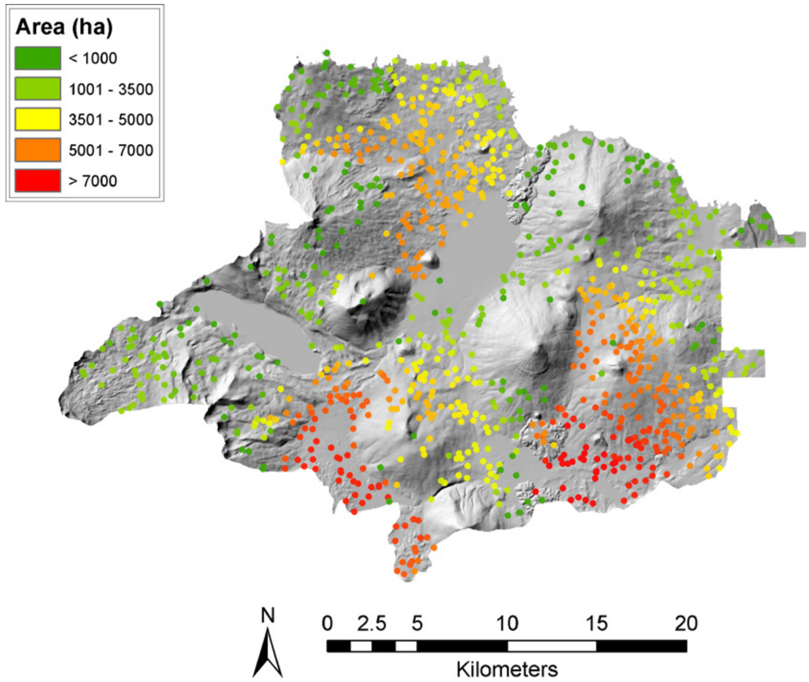

Fig. 4. Map of the Five Buttes study area showing ignition locations for 1000 simulated wildfires. Each ignition point is color rendered to indicate the size of the wildfire (ha) generated by the ignition as determined with FlamMap.

areas of high burn probability associated with major wildfire flow paths obtained from the FlamMap minimum travel time simulation (Figs. 6 and 7). Fire ‘‘shadows’’ were evident on the north side of Odell and Davis Lakes (Fig. 6), and elsewhere. The lowest burn probability outside of the non-burnable portions of the study area was observed within the Davis fire perimeter (Figs. 1 and 6).

Like wildfire size, average burn probability decreased in a non-linear trend with increasing treatment intensity (Table 1). For instance, at the maximum treatment rate of 50% (TRT-50 scenario), average burn probability was reduced from 0.0135 to 0.0028. Burn probabilities for the spotted owl habitat stands were on average about double those for the entire study area (Table 1).

3.5. Probability of habitat loss

The average probability of habitat loss ranged from 0.0237 for the TRT-0 scenario to 0.0088 for the TRT-50 scenario (Table 1) and decreased non-linearly with increasing treatment area. The probabilities represent the average likelihood of habitat loss in a given pixel in the event of a wildfire of a size equal to the average simulated wildfire size. For instance, the probability of 0.0237 for TRT-0 represents the average likelihood of loss given a wildfire of 1680 ha, the average size for the TRT-0 scenario (Table 1). Probability of habitat loss was higher than the average burn probability due to the higher overall burn probabilities within the spotted owl habitat (Table 1). Spatial variation in the probability of habitat loss was

Table 2
Area distribution of wildfire intensity averaged over the 1000 simulated wildfires for two (TRT-0, TRT-20) of the six treatment scenarios studied

Flame length interval (m)	Study area (% of total)		Owl habitat (% of total)	
	TRT-0	TRT-20	TRT-0	TRT-20
<0.5	21.5	28.0	21.9	27.0
0.5–1.0	14.2	12.9	14.5	12.8
1.0–1.5	19.3	20.9	19.3	21.6
1.5–2.0	17.8	15.9	17.8	16.2
2.0–2.5	12.6	10.5	12.6	10.8
2.5–3.0	6.2	5.6	5.9	5.4
3.0–3.5	3.8	3.1	3.7	3.2
3.5–4.0	2.0	1.5	2.0	1.6
4.0–4.5	0.9	0.6	1.0	0.7
4.5–5.0	0.5	0.5	0.6	0.6
>5.0	0.3	0.2	0.3	0.2

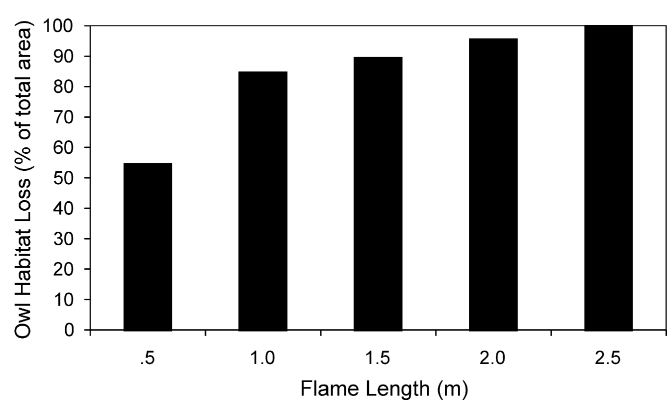

Fig. 5. Cumulative loss of spotted owl habitat as a function of flame length. Data were obtained by simulating fire in each owl habitat stand at a range of flame lengths and determining the flame length threshold at which the stand no longer met habitat criteria.

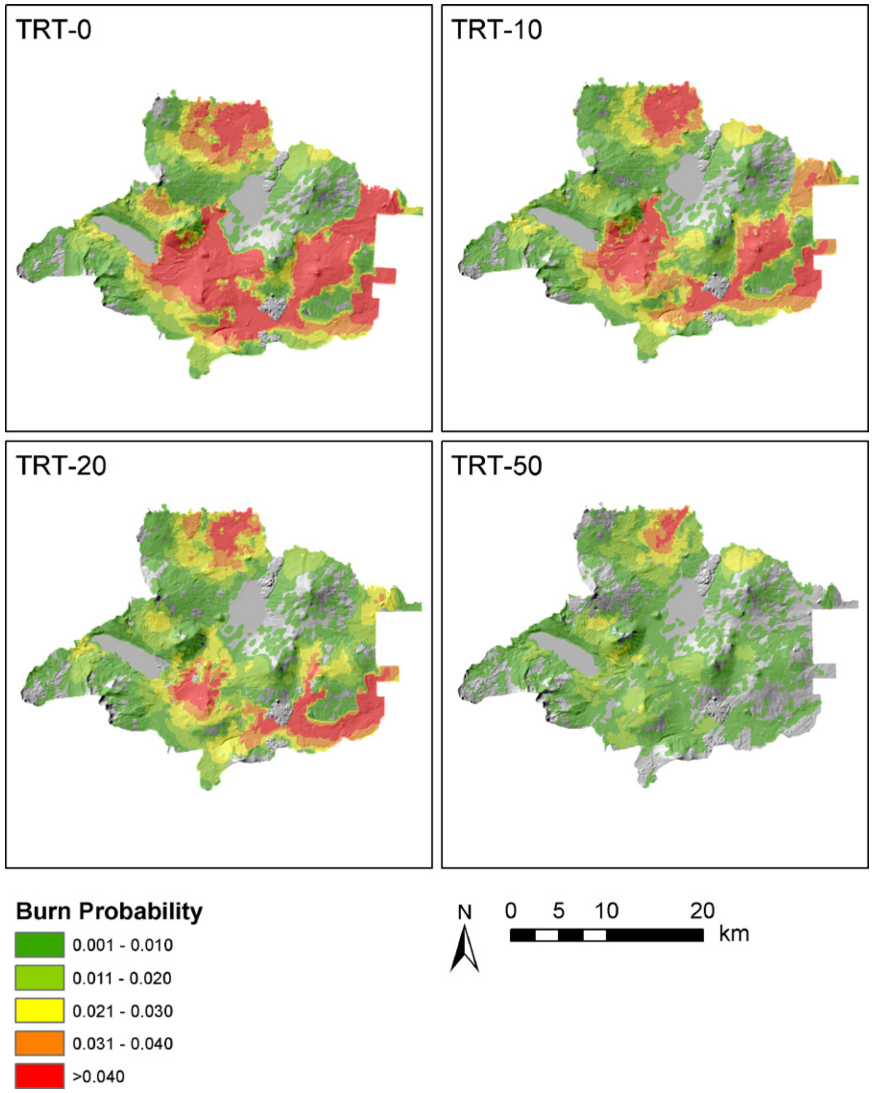

Fig. 6. Map of the Five Buttes study area showing burn probabilities for four of the six management scenarios examined in the study (TRT-0, TRT-10, TRT-20, TRT-50). The management scenarios applied fuel treatments to 0%, 10%, 20% and 50% of the study area, respectively. Burn probability for a given pixel was calculated as the number of fires in proportion to the total simulated fires.

substantial (Fig. 8) and was closely patterned after burn probability. The effect of treatment on the probability of habitat loss also exhibited considerable spatial variation (Fig. 8), even at low treatment levels. For instance, comparing TRT-0 and TRT-20, the fuel treatments substantially reduced the probability of loss in the spotted owl habitat stands immediately south of Davis Lake, and to a lesser extent elsewhere in the project area.

3.6. Expected habitat loss

Expected habitat loss, calculated as the product of the probability of habitat loss and the area of habitat ranged from a high of 218 for the TRT-0 scenario to 81 ha for the TRT-50 scenario (Table 1; Fig. 9). Thus, the simulations suggest that a random ignition in the study area burning for 24 h under conditions similar to the Davis fire would burn an average area of 1680 ha (Table 1) and eliminate 218 ha of habitat, or about 2.4% of the habitat in the study area. Expected loss of spotted owl habitat was substantially reduced between the TRT-0 and TRT-50 scenarios (Fig. 9), with a steep reduction between the TRT-0 and TRT-10 scenarios.

4. Discussion

The wildfire risk analysis system presented here can be used to analyze proposed strategies for mitigating wildfire risk to late successional forests in the Pacific Northwest (Spies et al., 2006). The application of quantitative risk assessment tools to analyze the potential resource impacts from wildfire has been advocated in many recent papers (e.g., US-EPA, 1998; Fairbrother and Turnley, 2005; Finney, 2005; Gonzalez et al., 2005; Irwin and Wigley, 2005; O'Laughlin, 2005; Roloff et al., 2005; Scott, 2006; Kerns and Ager, 2007). However, wildfire risk analysis tools are lacking within Federal land management agencies in the USA (GAO, 2004), making it

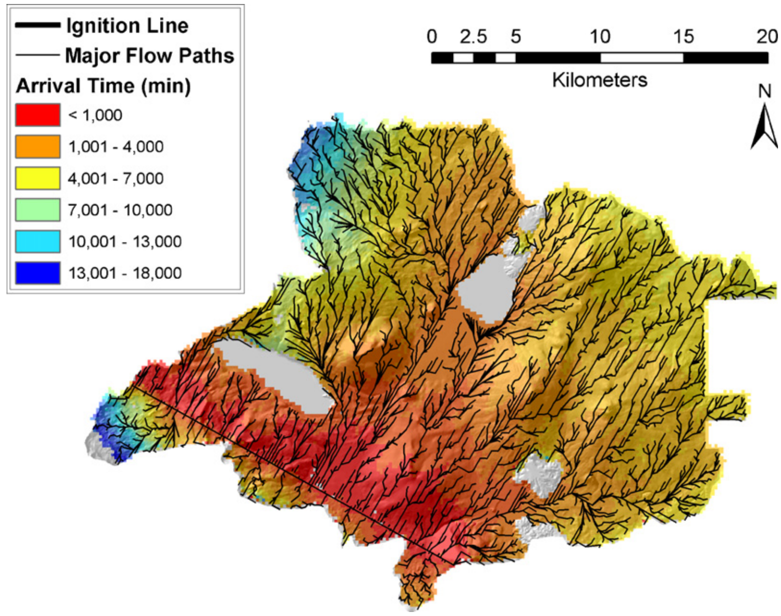

Fig. 7. Map of the Five Buttes study area showing fire spread calculations from FlamMap for a line ignition along the southwest perimeter. Color shading indicates wildfire arrival time (minutes). Major wildfire flow paths (black lines) indicate the major fire paths given a line ignition along the southwest edge of the study area as calculated in FlamMap. The fire conditions for the line ignition were the same as those used for the burn probabilities.

difficult for land managers to evaluate the effectiveness of proposed mitigation investments. While our modeling system does not yield an assessment of absolute wildfire risk, i.e., the likelihood of a future wildfire, the approach does provide a quantitative framework to analyze potential losses and benefits from specific wildfire events, and a method to quantify the effectiveness of landscape fuel treatment scenarios while recognizing fire spread, intensity and effects. Furthermore, the risk analysis system presented is built with models that are regularly used by Forest Service and other public land management agencies in the USA. The processing of fuel treatment alternatives with the FlamMap program in particular provides a battery of spatial information on potential wildfire behavior, including burn probabilities, major wildfire flow paths and arrival time, collectively providing a robust set of information for measuring the performance of landscape fuel treatment designs.

It is important to recognize the difference between burn probabilities estimated in the current study and empirical estimates of past and future wildfire likelihoods. In the latter (Preisler et al., 2004; Mercer and Prestemon, 2005; Brillinger et al., 2006), wildfire occurrence data were used to develop statistical models to explain the effects of explanatories like weather, location and time on the probability of ignition and fire growth. In contrast, burn probabilities as estimated in the present study were used to compare the effects of management and examine spatial variation in wildfire risk within the study area. The quantitative assessment of future wildfire risk over large areas (e.g., National Forests, 500,000 ha) and the efficient allocation of fuel treatment investments to planning units and watersheds remains a challenging problem. Other variables could be included in the current modeling framework to estimate burn probabilities that better reflect future wildfire occurrence (Miller, 2003; Parisien et al., 2005; Finney, 2006). However, seasonal variability in weather, suppression resources, and other factors will make this a difficult problem.

For the Five Buttes study area, average burn probability for the untreated landscape (0.0135) was about six times larger than the burn probability estimated from fire occurrence data for the Deschutes National Forest (0.0022, Finney, 2005) over the period of 1910–2003. However, considering the modeled fire as an escaped fire, which has approximately a 0.05 probability among all fires (Finney et al., 2006), the average burn probability is about 0.0007, which is about a third of the long-term average. An inherent downward bias in our burn probability estimate comes from an edge effect that eliminates the contribution of fires that migrate into the study area from ignitions elsewhere. Until we factor spatio-temporal data on ignitions, escape, burn periods and temporal sequences of weather conditions (Parisien et al., 2005), it is difficult to relate simulation estimates to absolute wildfire probabilities within the study area. However, on a relative basis, maps of burn probability and expected loss can provide a wealth of spatially explicit information on potential fire behavior that can be integrated into a variety of risk analyses to support landscape fuel treatment design.

The loss of northern spotted owl habitat to wildfire in the late successional dry forests of the Pacific Northwest is an ongoing problem in the overall conservation strategy for the spotted owl. The methods and results of the current study can help guide the development of strategies to mitigate wildfire risk to remaining late successional reserves. Maps of burn probabilities, wildfire flow paths and optimized treatment locations (Finney, 2006) within and around late successional reserves can provide land managers with the information to analyze mitigation options to address the growing threat from large fires. Wildfire probability

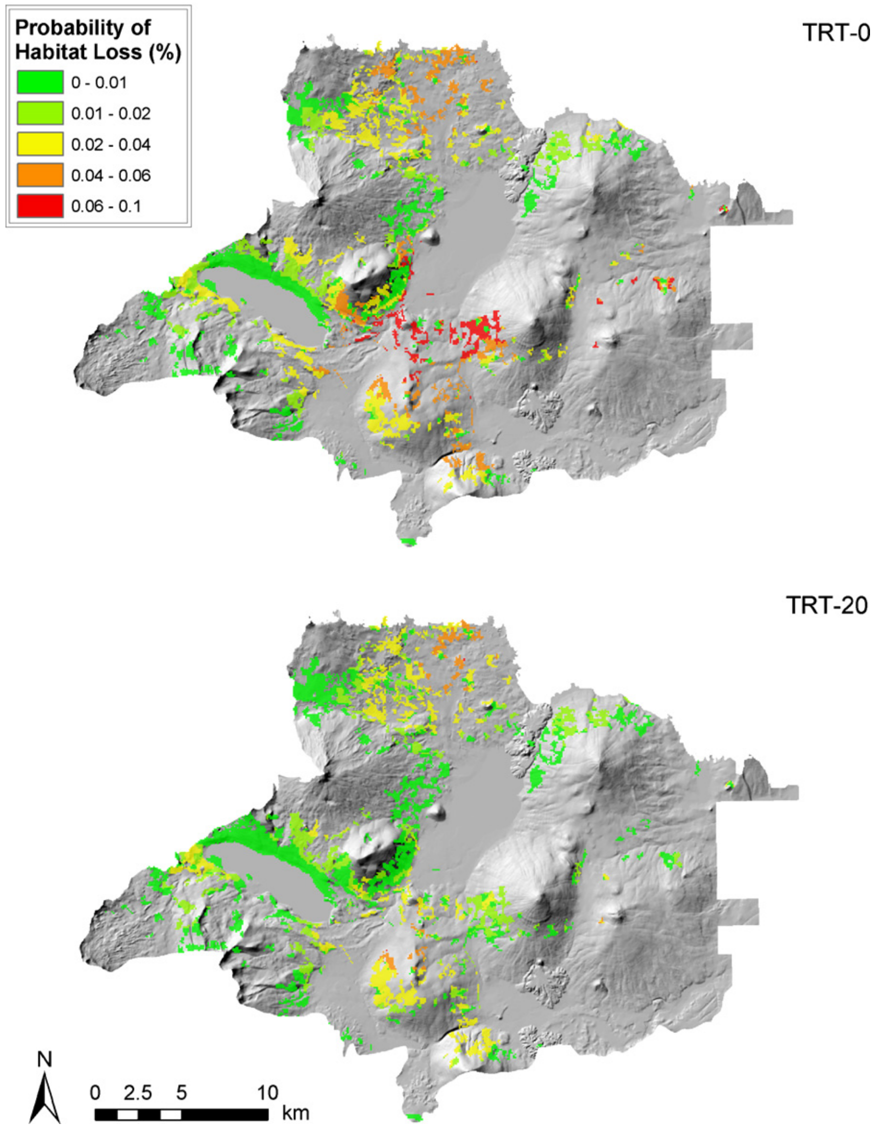

Fig. 8. Map of the Five Buttes study area showing the probability of owl habitat loss for two of the six treatment scenarios (TRT-0, TRT-20) analyzed in the study. The probability of loss is a subset of the burn probability (Fig. 6), and is the probability of a fire with sufficient intensity to eliminate forest conditions required for owl habitat as described in the text.

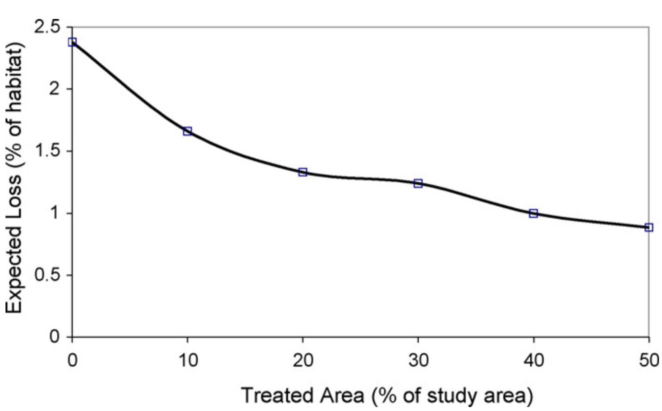

Fig. 9. Relationship between expected loss (ha) and area treated (% of study area) for the six management scenarios simulated in the study. Expected loss is the product of probability and area of habitat lost expressed as a percent of the maximum expected loss in the no treatment (TRT-0) scenario.

shadows on the lee sides of lava field, lakes and other non-burning features in the landscape should be considered in the future modification of the existing habitat network here and elsewhere within the range of the spotted owl. In the Five Buttes area, we observed higher burn probabilities for spotted owl habitat stands compared to the overall study area, a finding that persisted after simulating fuel treatment in adjacent stands. Whether this result stems from fuel conditions within spotted owl habitat stands or their location relative to major fire flow paths in the study area could not be determined in the current study.

A key difference between our study and previous modeling of spotted owl habitat-wildfire interactions (Calkin et al., 2005; Hummel and Calkin, 2005; Lee and Irwin, 2005; Roloff et al., 2005) is that we did not apply treatments within spotted owl habitat. The intent was to demonstrate that substantial reduction in wildfire risk as measured by probabilities or expected habitat loss can be realized by strategically locating treatments to reduce fire spread to spotted owl habitat stands. Application of spatial treatment optimization (Finney, 2006), and allowing treatments within spotted owl habitat in the present study would have substantially decreased the expected habitat loss at a given treatment intensity. Although treating within habitat conservation reserves is controversial, the long-term benefits of managing spotted owl habitat in dry forests has been argued in numerous studies as a means to reduce risk from natural disturbances (Agee, 2002; Roloff et al., 2005). Additional work to explore these and related questions will further address the role of forest management in the conservation of spotted owl habitat.

The methods we describe can be directly applied to other biological conservation problems where habitat requirements are defined in terms of forest structure and composition. Habitat management criteria exist for many species of conservation concern in the western USA including pileated woodpeckers (*Dryocopus pileatus*), Canada lynx (*Lynx canadensis*) and Chinook salmon (*Oncorhynchus tshawytscha*), to name a few. Flame length thresholds can be identified with FVS-FFE as done in the present study for an array of stand structural attributes calculated by FVS. The methods can also be applied to examine how wildfire might impact forest restoration goals to create fire resilient forest composition and structure. Expected loss could also be examined for other deleterious wildfire effects such as smoke emissions, soil heating, duff consumption (Reinhardt et al., 1997) and hydrologic effects (O'Laughlin, 2005; Roloff et al., 2005). Many other valuation scenarios could be evaluated, including ones that consider financial values like treatment costs, potential timber revenues and projected changes to wildfire suppression costs (Hummel and Calkin, 2005).

The risk analysis system can also be applied to analyze temporal tradeoffs in wildfire risk mitigation, i.e., whether potential short-term impacts from fuel treatments are offset by long-term reduction in wildfire risk (Finney et al., 2006; Irwin and Wigley, 2005; O'Laughlin, 2005; Roloff et al., 2005). This ''relative risk'' problem, as outlined by O'Laughlin (2005) and studied by Roloff et al. (2005), has yet to be examined in a probabilistic framework, and remains a significant policy issue in conservation efforts for the spotted owl.

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